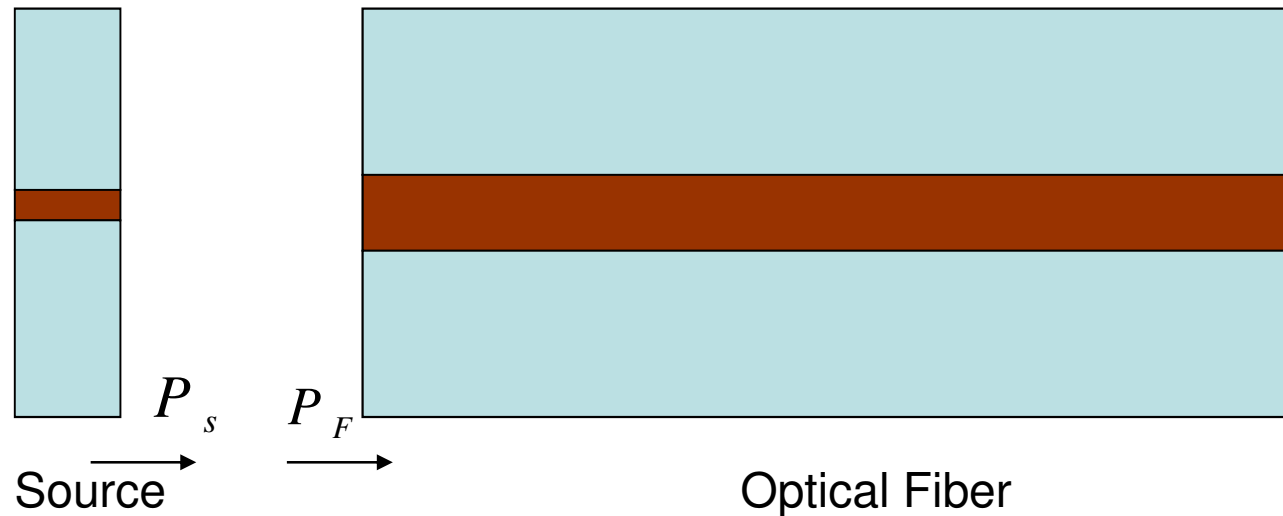


Chapter 5

Power Launching and Coupling

Coupling Efficiency

$$\eta = \frac{\text{power coupled into the fiber}}{\text{power emitted from the source}} = \frac{P_F}{P_s} \quad [5-1]$$



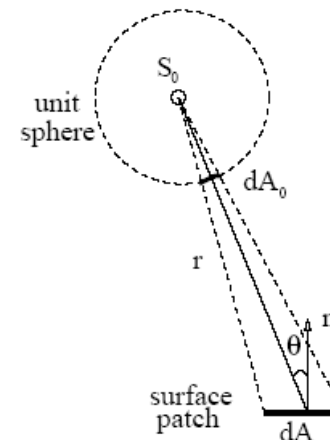
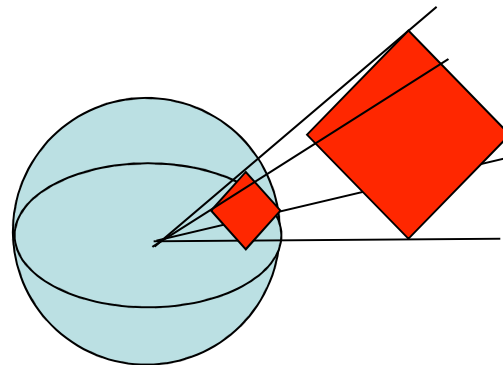
Source to fiber power launching

Optical output of a luminescent source is usually measured by its **radiance B** at a given diode current.

Radiance: It is the optical power radiated into a unit solid angle per unit emitting surface area and is generally specified in terms of watts per square centimeter per steradian.

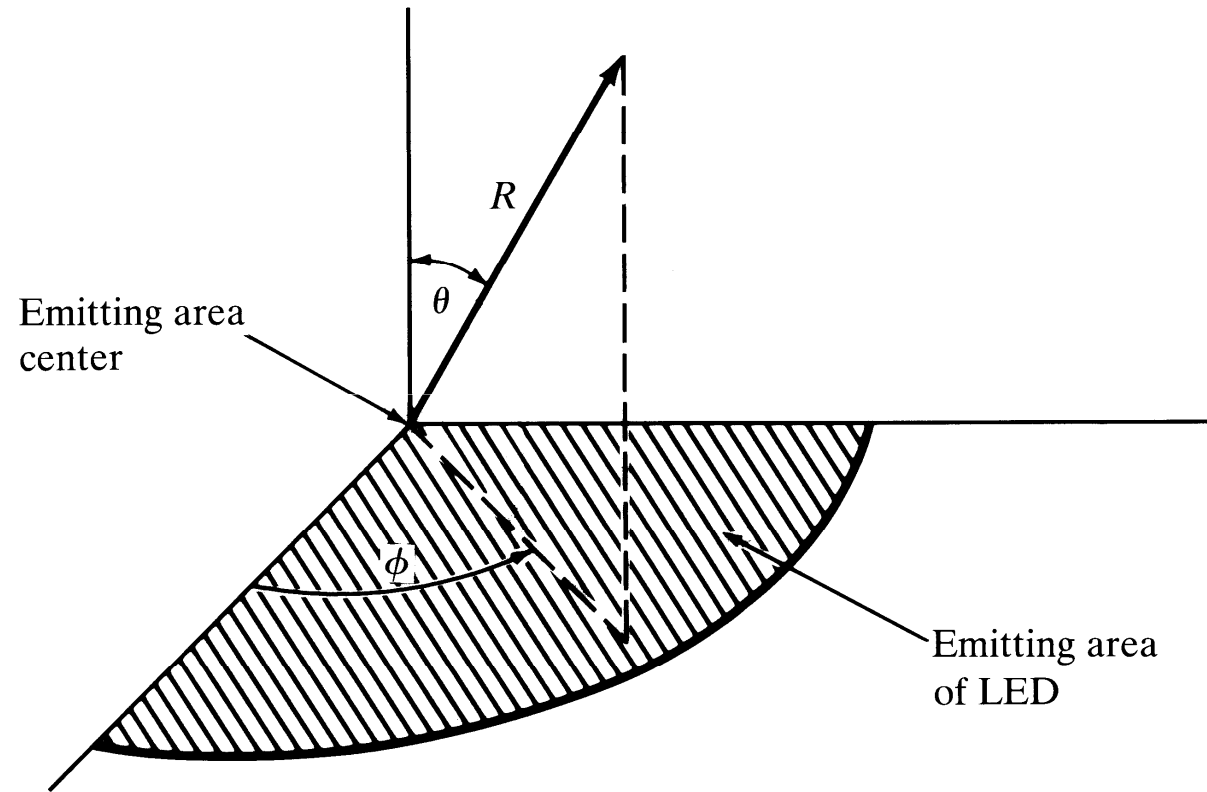
Radiance = Power / per unit solid angle x per unit emitting surface area

Solid angle is defined by the projected area of a surface patch onto a unit sphere of a point.



The angle that, seen from the center of a sphere, includes a given area on the surface of that sphere. The value of the solid angle is numerically equal to the size of that area divided by the square of the radius of the sphere

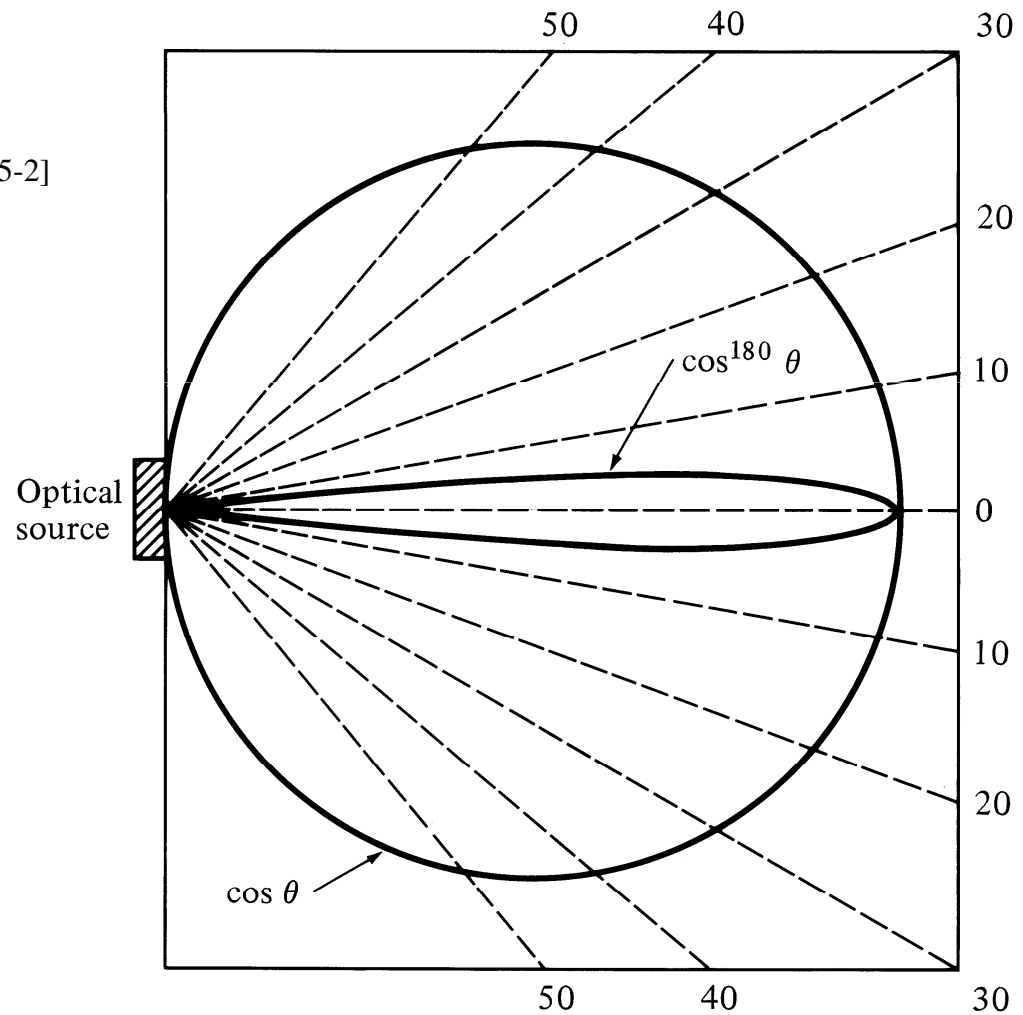
Radiance (Brightness) of the source



- B = Optical power radiated from a unit area of the source into a unit solid angle [watts/(square centimeter per stradian)]

Surface emitting LEDs have a Lambertian output pattern:

$$B(\theta, \phi) = B_0 \cos \theta \quad [5-2]$$



Edge emitting LEDs and laser diodes radiation pattern

$$\frac{1}{B(\theta, \phi)} = \frac{\sin^2 \phi}{B_0 \cos^T \theta} + \frac{\cos^2 \phi}{B_0 \cos^L \theta} \quad [5-2]$$

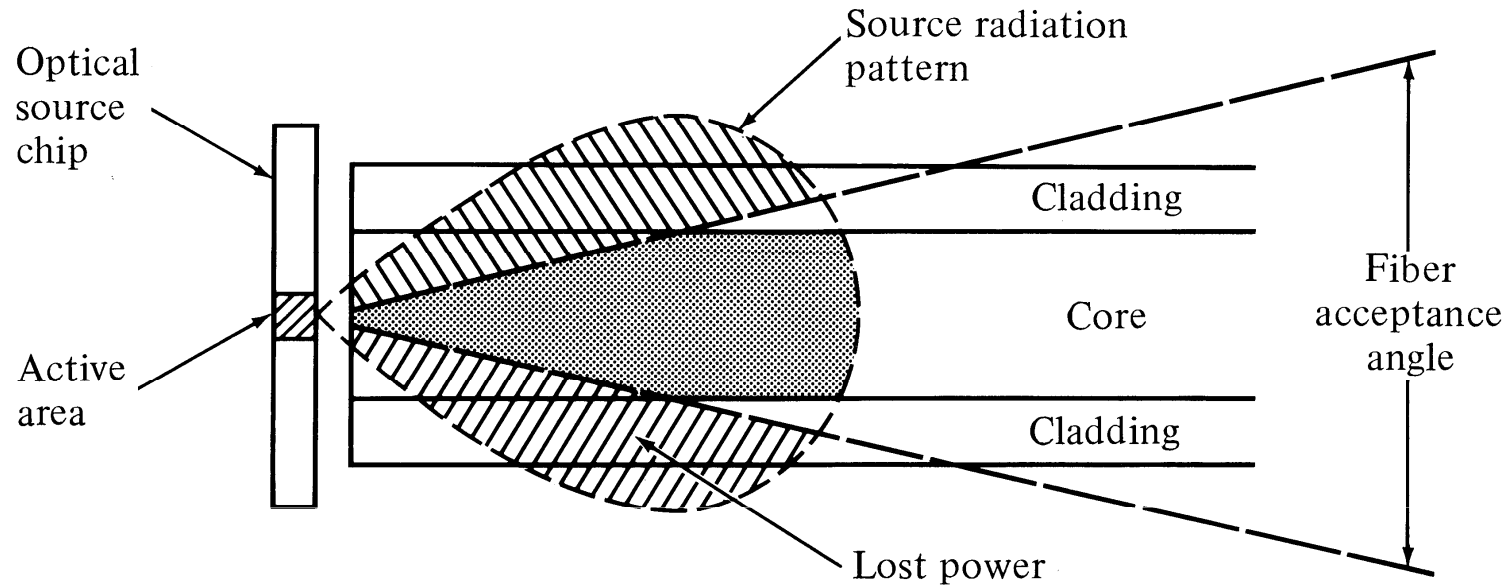
For edge emitting LEDs, $L=1$.

For a laser diode that has a lateral ($\phi=0^\circ$) half-power beamwidth of $2\theta=10^\circ$,

$$B(\theta = 5^\circ, \phi = 0^\circ) = B_0 \cos^L(5^\circ) = \frac{1}{2} B_0;$$

$$L = \frac{\log 0.5}{\log(\cos 5^\circ)} = 182$$

Power Coupled from source to the fiber



A_s and Ω_s : area and solid emission angle of the source

A_f and Ω_f : area and solid acceptance angle of fiber

$$P_F = \int_{A_f} \left[\int_{\Omega_f} B(A_s, \Omega_s) d\Omega_s \right] dA_s$$

[5-3]

$$r_m = \begin{cases} a & r_s > a \\ r_s & r_s < a \end{cases} \quad = \int_0^{r_m} \int_0^{2\pi} \left[\int_0^{2\pi} \int_0^{\theta_{0\max}} B(\theta, \phi) \sin \theta d\theta d\phi \right] d\theta_s r dr$$

Power coupled from LED to the Fiber

$$\begin{aligned} P &= \int_0^{r_s} \int_0^{2\pi} \left(2\pi B_0 \int_0^{\theta_{0\max}} \cos \theta \sin \theta d\theta \right) d\theta_s r dr \\ &= \pi B_0 \int_0^{r_s} \int_0^{2\pi} \sin^2 \theta_{0\max} d\theta_s r dr \\ &= \pi B_0 \int_0^{r_s} \int_0^{2\pi} \text{NA}^2 d\theta_s r dr \end{aligned}$$

$$P_{\text{LEDstep}} = \pi^2 r_s^2 B_0 (\text{NA})^2 \approx 2\pi^2 r_s^2 B_0 n_1^2 \Delta$$

[5-5]

Power coupling from LED to step-index fiber

- Total optical power from LED:

$$P_s = A_s \int_0^{2\pi} \int_0^{\pi/2} B(\theta, \phi) \sin \theta d\theta d\phi$$

$$P_s = \pi r_s^2 2\pi B_0 \int_0^{\pi/2} \cos \theta \sin \theta d\theta = \pi^2 r_s^2 B_0$$

[5-6]

$$P_{\text{LED,step}} = \begin{cases} P_s (\text{NA})^2 & \text{if } r_s \leq a \\ \left(\frac{a}{r_s}\right)^2 P_s (\text{NA})^2 & \text{if } r_s \geq a \end{cases}$$

[5-7]

Power coupling from LED to graded-index fiber

- Power coupled from the LED to the graded indexed fiber is given as

$$\begin{aligned} P_{LED,gin} &= 2\pi^2 B_o \int_0^{r_s} [n^2(r) - n_2^2] r dr; n(r) = NA(0) \sqrt{1 - (r/a)^\alpha} \\ &= 2P_s n_1^2 \Delta \left[1 - \frac{2}{\alpha + 2} \left(\frac{r_s}{a} \right)^\alpha \right] \end{aligned}$$

- If the medium between source and fiber is different from the core material with refractive index n , the power coupled into the fiber will be reduced by the factor

$$R = \left(\frac{n_1 - n}{n_1 + n} \right)^2$$

Power Launching Vs Wavelength

- Optical power only depends on the radiance and not on the wavelength of the mode. For a graded index fiber number of modes is related to the wavelength as

$$M = \frac{\alpha}{\alpha + 2} \left(\frac{2\pi a n_1}{\lambda} \right)^2 \Delta$$

- So twice as many modes propagate for 900 nm as compared to 1300 nm but the radiated power per mode from a source is

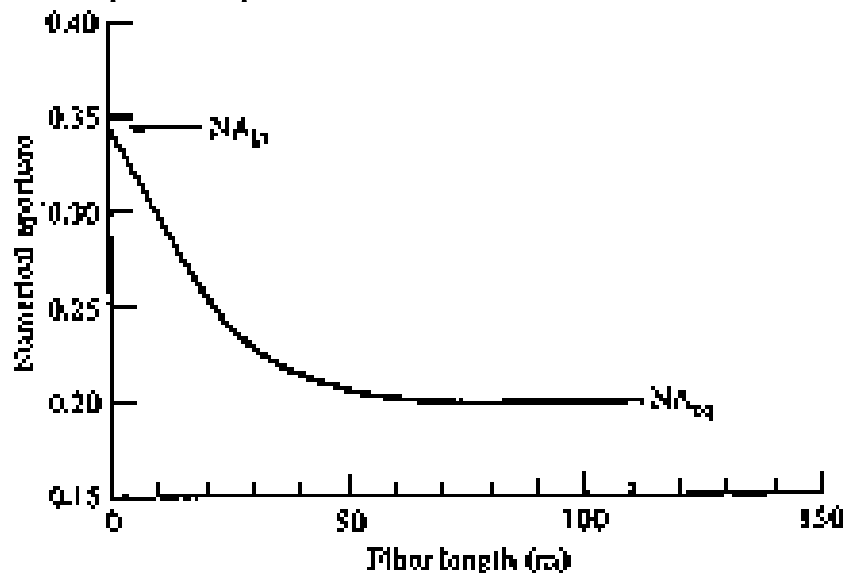
$$\frac{P_s}{M} = B_o \lambda^2$$

- So twice as much power is launched per mode for 1300nm as compared to the 900nm

Equilibrium Numerical aperture

- For fibers with flylead attachments the connecting fiber should have the same NA. A certain amount of loss occurs at this junction which is almost 0.1 – 1dB. Exact loss depends on the connecting mechanism.
- Excess power loss occurs for few tens of meters of a multimode fiber as the launched modes come to the equilibrium.
- The excess power loss is due to the non propagating modes
- The loss is more important for SLED.
- Fiber coupled lasers are less prone to this effect as they have very few non propagating modes.
- The optical power in the fiber scales as

$$P_{eq} = P_{50} \left(\frac{NA_{eq}}{NA_{in}} \right)^2$$

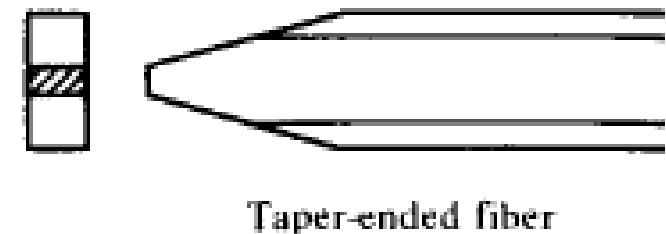
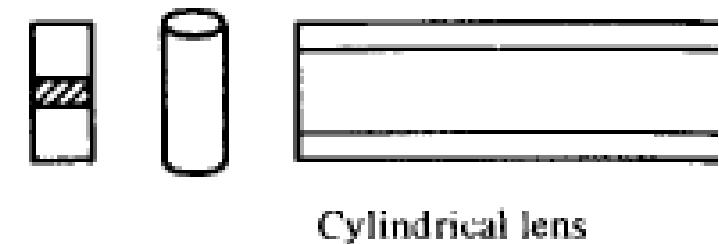
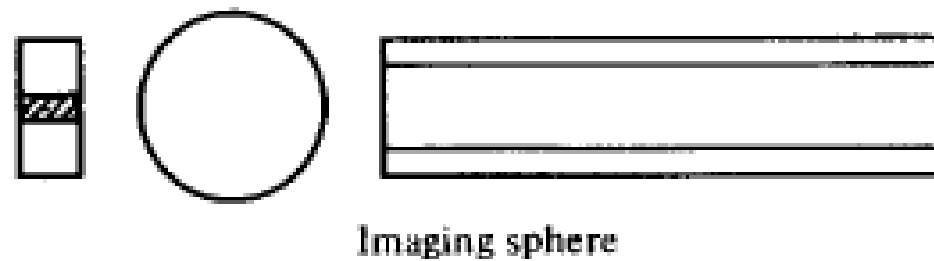
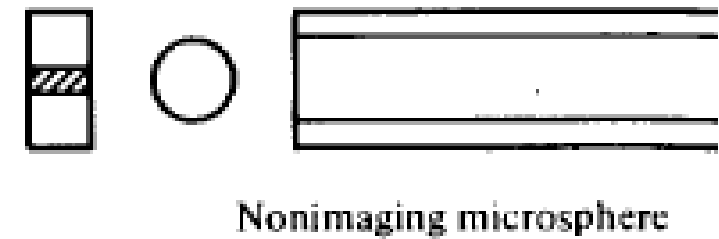
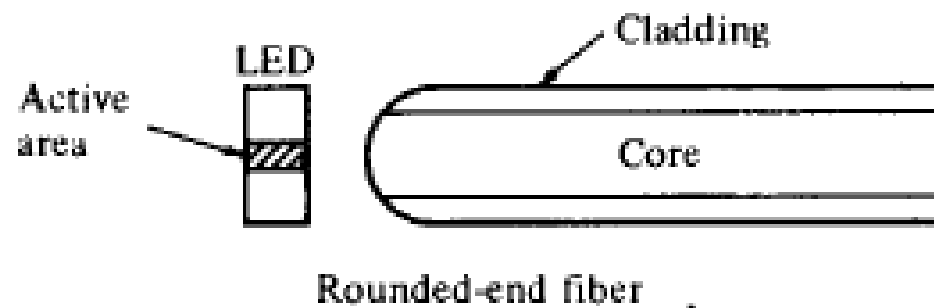


P_{50} : optical power measured at 50 m. (distance at which modes become equilibrium)

Lensing Scheme for Coupling Improvement

Several Possible lensing schemes are:

1. Rounded end fiber
2. Nonimaging Microsphere (small glass sphere in contact with both the fiber and source)
3. Imaging sphere (a larger spherical lens used to image the source on the core area of the fiber end)
4. Cylindrical lens (generally formed from a short section of fiber)
5. Spherical surfaced LED and spherical ended fiber
6. Taper ended fiber.



Examples of possible lensing scheme used to improve optical source to fiber coupling efficiency

Lensing Scheme for Coupling Improvement

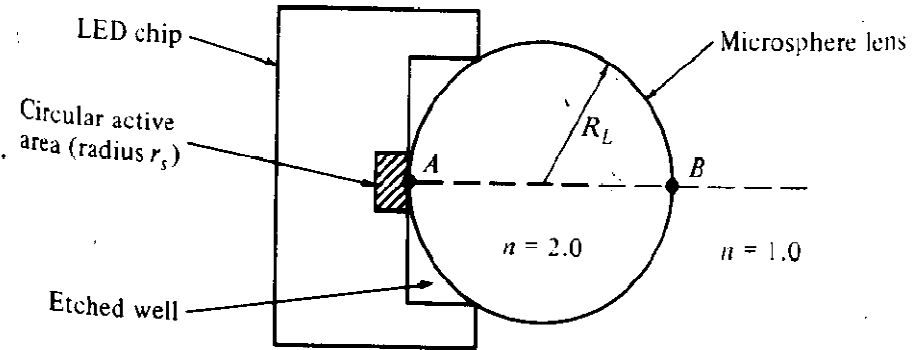
Problem in using lens:

One problem is that the lens size is similar to the source and fiber core dimensions, which introduces fabrication and handling difficulties.

In the case of taper end fiber, the mechanical alignment must be carried out with great precision

Non Imaging Microsphere

- Use for surface emitter is shown
- Assumptions: refractive indices shown in the fig. and emitting area is circular
- To collimate the output from the LED, the emitting surface should



be located at the focal point of the lens which can be found as

$$\frac{n}{s} + \frac{n'}{q} = \frac{n' - n}{r}$$

where s and q are object and image distances as measured from the lens surface, n is the refractive index of the lens, n' is the refractive index of the outside medium and r is the radius of curvature of the lens surface.

The following sign conventions are used

1. Light travels from left to right
2. Object distances are measured as positive to the left of a vertex and negative to the right
3. Image distances are measured as positive to the right of a vertex and negative to the left
4. All convex surfaces encountered by the light have a positive radius of curvature, and concave surfaces have a negative radius.

For these conventions, we can find the focal point for the right hand surface of the lens shown in the last fig. We set $q = \text{infinity}$, solve for s yields

$$s = f = 2R_L$$

So the focal point is at point A. Magnification M of the emitting area is given as

$$M = \frac{\pi R_L^2}{\pi r_s^2} = \left(\frac{R_L}{r_s} \right)^2$$

Using eq. 5.4 one can show that, with the lens, the optical power P_L that can be coupled into a full aperture angle 2θ is given by

$$P_L = P_s \left(\frac{R_L}{r_s} \right)^2 \sin^2 \theta$$

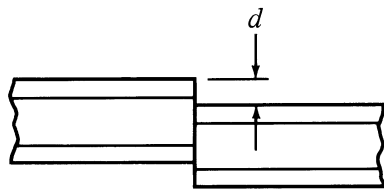
For the fiber of radius a and numerical aperture NA, the maximum coupling efficiency $\eta_{\max}$ is given by

$$\eta_{\max} = \begin{cases} \left(\frac{a}{r_s} \right)^2 (\text{NA})^2 & \text{for } \frac{r_s}{a} > \text{NA} \\ 1 & \text{for } \frac{r_s}{a} \leq \text{NA} \end{cases}$$

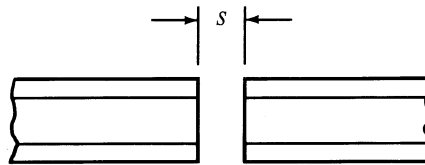
So when the radius of the emitting area is larger than the fiber radius, there'll be no improvement in the coupling efficiency with the use of lens

Mechanical Misalignment

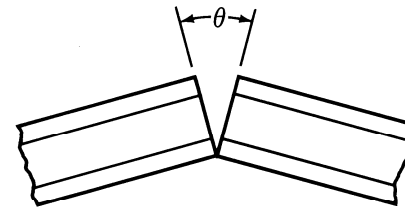
- Mechanical alignment is the major problem when joining two fibers considering their microscopic size.
- A standard multimode GIN fiber core is 50 - 100 μm in diameter (thickness of the human hair)
- Single mode fiber has core dia of 9 μm
- Radiation losses occur because the acceptance cone of the emitting fiber is not equal to the acceptance cone of the receiving fiber.
- Magnitude of radiation loss depends on the degree of misalignment
- Three different types of misalignment can occur
 - Longitudinal Separation
 - Angular misalignment
 - Axial displacement or lateral displacement



(a) Lateral (axial)



(b) Longitudinal (end separation)



(c) Angular

Axial displacement

- Most common misalignment is the axial displacement.
- It causes the greatest power loss

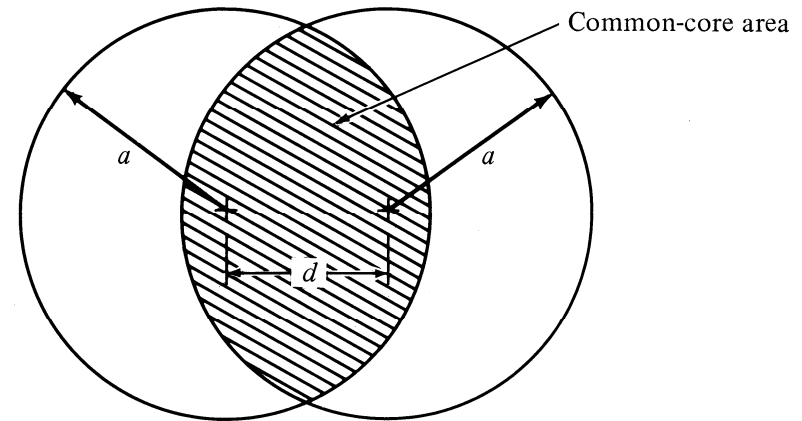


Illustration:

- Axial offset reduces the overlap area of the two fiber-core end faces
- This in turn reduces the power coupled between two fibers.

- To illustrate the effect of misalignment, consider two identical step-index fibers of radii a .
- Suppose the axes are offset by a separation d
- Assume there is a uniform modal power distribution in the emitting fiber.
- NA is constant for the two fibers so coupled fiber will be proportional to the common area A_{comm} of the two fiber cores

$$A_{comm} = 2a^2 \arccos \frac{d}{2a} - d \left(a^2 - \frac{d^2}{4} \right)^{1/2}$$

- For step index fiber, the coupling efficiency is simply the ratio of the common core area of the core end face area

$$\eta_{F,step} = \frac{A_{comm}}{\pi a^2} = \frac{2}{\pi} \arccos \frac{d}{2a} - \frac{d}{\pi a} \left[1 - \left(\frac{d}{2a} \right)^2 \right]^{1/2}$$

- For *Graded Index Fiber* the calculations for the power loss between two identical fibers is more complex since n varies across the end face of the core.
- The total power coupled in the common area is restricted by the NA of the transmitting or receiving fiber at the point, depending which one is smaller.
- If the end face of the GIN fiber is uniformly illuminated, the optical power accepted by the core will be that power which falls within the NA of the fiber.
- The optical power density $p(r)$ at a point r on the fiber end is proportional to the square of the local $NA(r)$ at that point

$$p(r) = p(0) \frac{NA^2(r)}{NA^2(0)}$$

Where $NA(r)$ and $NA(0)$ are defined by eqs. 2.80. $p(0)$ is the power density at the core axis which is related to the total power P in the fiber by

$$P = \int_0^{2\pi} \int_0^a p(r) r dr d\theta$$

We can use the parabolic index profile ($\alpha=2$) for which $p(r)$ will be given as

$$p(r) = p(0)[1 - \{r/a\}^2]$$

P will be calculated as

$$P = (\pi a^2 / 2) p(0)$$

The calculations of received power for GIN fiber can be carried out and the result will be

$$P_T \simeq P \left(1 - \frac{8d}{3\pi a} \right)$$

Where P is the total power in the transmitting fiber, d is the distance between two axes and a is the radius of fiber

The coupling loss for the offsets is given as

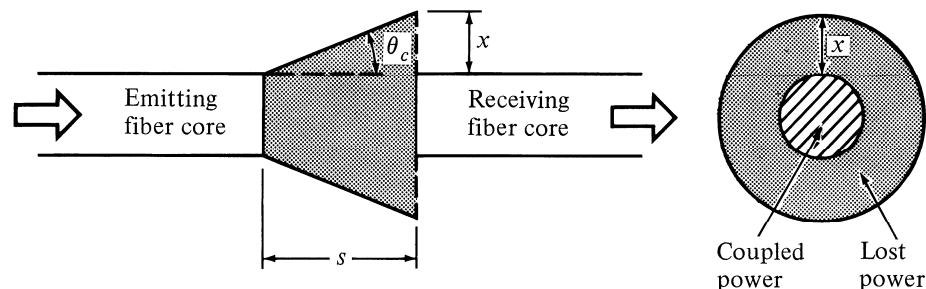
$$L_F = -10 \log \eta_F = -10 \log \frac{P_T}{P}$$

For Longitudinal misalignment:

For longitudinal misalignment of distance s , the coupling loss is given as

$$L_F = -10 \log \left(\frac{a}{a + s \tan \theta_c} \right)^2$$

Where s is the misalignment and θ_c is the critical acceptance angle of the fiber



Angular misalignment at the joint

When the axes of two fibers are angularly misaligned at the joint, the optical power that leaves the emitting fiber outside the acceptance angle of the receiving fiber will be lost. For two step index fibers with misalignment angle θ , the optical power loss at the joint will be

$$L_F = -10 \log \left(\cos \theta \left\{ \frac{1}{2} - \frac{1}{\pi} p (1 - p^2)^{1/2} - \frac{1}{\pi} \arcsin p \right. \right. \\ \left. \left. - q \left[\frac{1}{\pi} y (1 - y^2)^{1/2} + \frac{1}{\pi} \arcsin y + \frac{1}{2} \right] \right\} \right)$$

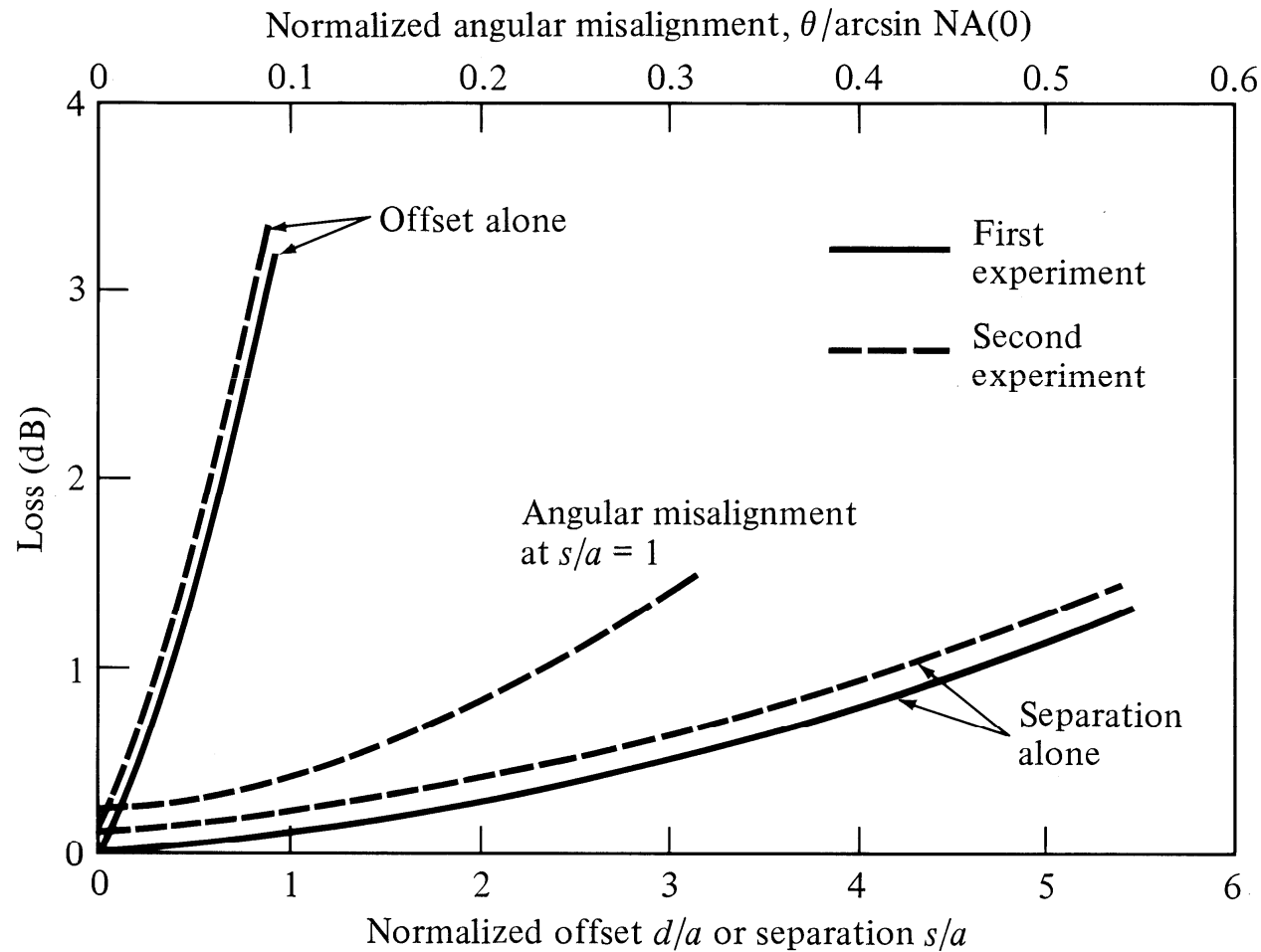
where

$$p = \frac{\cos \theta_c (1 - \cos \theta)}{\sin \theta_c \sin \theta}$$

$$q = \frac{\cos^3 \theta_c}{(\cos^2 \theta_c - \sin^2 \theta)^{3/2}}$$

$$y = \frac{\cos^2 \theta_c (1 - \cos \theta) - \sin^2 \theta}{\sin \theta_c \cos \theta_c \sin \theta}$$

Experimental comparison of Loss as a function of mechanical misalignment



Fiber Related Losses

Fiber losses are related to the

- Core diameter
- Core area ellipticity, numerical aperture
- Refractive index profiles
- Core-cladding concentricity

Fiber losses are significant for differences in core radii and NA

Different core radii: Loss is given as

$$L_F(a) = \begin{cases} -10 \log \left(\frac{a_R}{a_E} \right)^2 & \text{for } a_R < a_E \\ 0 & \text{for } a_R \geq a_E \end{cases}$$

Different NA: Power loss is given as

$$L_F(\text{NA}) = \begin{cases} -10 \log \left[\frac{\text{NA}_R(0)}{\text{NA}_E(0)} \right]^2 & \text{for } \text{NA}_R(0) < \text{NA}_E(0) \\ 0 & \text{for } \text{NA}_R(0) \geq \text{NA}_E(0) \end{cases}$$

Different core index profiles: Coupling loss will be given as

$$L_F(\alpha) = \begin{cases} -10 \log \frac{\alpha_R(\alpha_E + 2)}{\alpha_E(\alpha_R + 2)} & \text{for } \alpha_R < \alpha_E \\ 0 & \text{for } \alpha_R \geq \alpha_E \end{cases}$$